Black Holes and Host Galaxies of NLS1s

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Recently, reliable mass estimates for the central black holes in AGN became feasible due to emission-line reverberation techniques. Using this method as a calibrator, it is possible to determine black hole masses for a wide range of AGN, in particular NLS1s. Do NLS1s have smaller black holes than ordinary Seyfert 1 galaxies? Are their black holes smaller compared to the sizes of their host galaxies? Do they have larger L/M ratios? Do NLS1s have hotter accretion disks? I confront these questions with accretion disk theory and with the data, showing that the above may well be the case.

Key words: galaxies: active; quasars: general; quasars: emission lines; accretion disks; black holes

1 The spectrum-black hole mass relation for accretion disks

In the accretion disk paradigm for the power source of an AGN, the continuum luminosity and spectral temperature are related to the black hole mass by the relation

$$L_{46} \sim (E/10 \text{ eV})^4 M_8^{-2} (R/5R_\text{s})^2, \tag{1}$$

where E is the average photon energy, $R_\text{s} = 2GM/c^2 \approx 3 \times 10^{13} M_8$ cm is the Schwarzshild radius, and L_{46} is the bolometric luminosity. The temperature in the black body part of the disk is

$$T(R) \approx \left(\frac{3GM\dot{M}}{8\pi\sigma R^3}\right)^{1/4} \approx 6 \times 10^5 \left(\frac{\dot{m}}{M_8}\right)^{1/4} r^{-3/4} \text{ K}, \tag{2}$$

where $r = R/R_\text{s}$ and $\dot{m} = \dot{M}/\dot{M}_\text{Edd} \approx 2(\dot{M}/M_\odot \text{ yr}^{-1}) M_8^{-1} (\epsilon/0.1)^{-1}$ is the accretion rate in units of the Eddington accretion rate (ϵ being the efficiency), so that $\dot{m} = 1$ at the Eddington limit. When the accretion rate approaches the Eddington rate, the thin disk solution in the inner region is probably not valid, and it has to be replaced by a hot disk solution (e.g. Wandel & Liang 1991). The spectrum of a multi-black body accretion disk is given by integrating the local black body spectrum over the entire disk, $L_\nu \approx \int_{R_\mathrm{t}}^{R_\mathrm{out}} 2\pi R B_\nu[T(R)]dR$, where $B_\nu(T)$ is the Planck function and R_t is the transition radius from the black body region to the inner optically thin region. If the disk is radially extended ($R_\mathrm{out}/R_\mathrm{t} \gg 1$), the spectrum is almost flat ($\sim \nu^{1/3}$) and cuts off beyond $h\nu_\mathrm{co} \approx 3kT(R_\mathrm{t})$, approximately

$$L_\nu \approx A \left(\frac{\nu}{\nu_\mathrm{co}}\right)^{1/3} \exp\left(-\frac{\nu}{\nu_\mathrm{co}}\right), \tag{3}$$

where A and ν_co are the normalization and cutoff frequency. For a Kerr black hole, Malkan (1990) finds $\nu_\mathrm{co} = (2.9 \times 10^{15}\ \mathrm{Hz})\dot{M}_{0.1}^{1/4} M_8^{-1/2}$, where $\dot{M}_{0.1} = \dot{M}/0.1 M_\odot\ \mathrm{yr}^{-1}$. This can be written as

$$h\nu_\mathrm{co} = (6\ \mathrm{eV})\dot{m}^{1/4} M_8^{-1/4} = (20\ \mathrm{eV}) L_{46}^{1/4} M_8^{-1/2}, \tag{4}$$

where L_{46} is the *observed* luminosity, and we have included a bolometric correction of 10. If the black body region extends down to a radius R_t, and the EUV cutoff energy is E_co, then

$$M_8 \approx 2.5 (E_\mathrm{co}/10\ \mathrm{eV})^{-2} L_{46}^{1/2} (R_\mathrm{t}/5R_\mathrm{s})^{-1}. \tag{5}$$

When the black body regime extends close to the inner disk edge, the spectrum for the Schwarzshild case peaks at the photon energy $E \gtrsim (17\ \mathrm{eV}) L_{46}^{1/4} M_8^{-1/2}$. For a Kerr black hole (eq. 4) $E \gtrsim (20\ \mathrm{eV}) L_{46}^{1/4} M_8^{-1/2}$. Plotting the cutoff frequency versus the luminosity, one can infer the mass. Alternatively, if the mass can be estimated independently, it is possible to estimate the cutoff frequency (Fig. 1; cf. Wandel & Petrosian 1988).

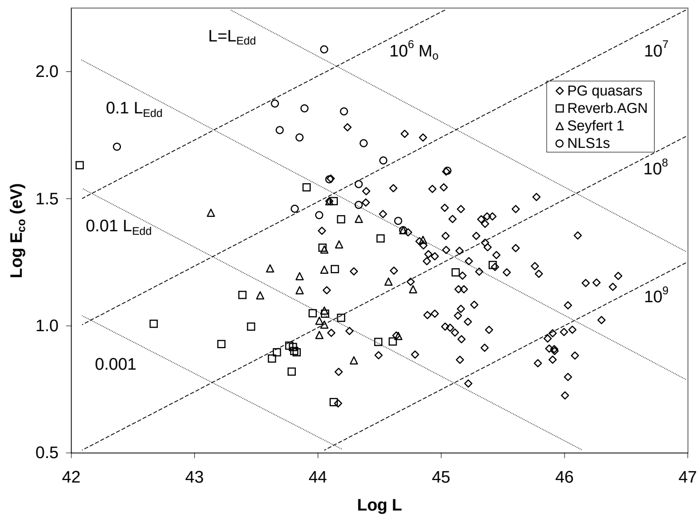

Figure 1. The peak (or cutoff) energy for an accretion disk spectrum versus the monochromatic luminosity at 5100 Å. Diagonal dashed lines indicate constant black hole masses, and diagonal dotted lines indicate the Eddington ratio. Diamonds indicate PG quasars (Boroson & Green 1992), squares—Seyfert 1 galaxies, triangles—AGN with BLR reverberation data, circles—NLS1s (Boller, Brandt & Fink 1996).

2 Black Hole Masses

It is possible to estimate the black hole mass from the broad emission-line profile, assuming the velocity width is induced by a Keplerian velocity dispersion. When the broad line region size is estimated by reverberation mapping, this technique is particularly reliable. Wandel, Peterson & Malkan (1999) have used a sample of AGN with reverberation data to calibrate the mass estimate obtained from photoionization models, finding the relation

$$M_8 \approx 0.4 \left(\frac{L_{46}}{U n_{10}} \right)^{1/2} v_3^2, \tag{6}$$

where U is the ionization parameter, n_{10} is the density in units of 10^{10} cm^{-3}, and v_3 is the Hβ FWHM in units of 10^3 km s^{-1}. Using this calibrated relation, it is possible to estimate black hole masses for large samples, even without reverberation data (Wandel, Malkan & Peterson, in preparation). Combining equations 6 and 4, we have

$$E_{\rm co} \approx (40 \text{ eV})(Un_{10})^{-1/4} v_3^{-1}, \tag{7}$$

which is independent of luminosity and only weakly dependent on the unknown parameters U and n. Using eq. 7 with Un_{10}=1, we find the mass and cutoff energy distribution for a large sample of quasars, Seyfert 1 galaxies and NLS1s (Fig. 1). Note that $E_{\rm co}$ is anticorrelated with the mass, and in particular that different AGN categories group in different regions of the L-$E_{\rm co}$ plane: quasars have more massive black holes and low cutoff energies, Seyfert 1 galaxies have intermediate black hole masses (10^7–$10^8 M_\odot$), and NLS1s have low black hole masses (10^6–$10^7 M_\odot$) and high cutoff energies. This is consistent with the large soft X-ray excesses observed for many of the NLS1s. The diagonal dotted lines in Fig. 1 give the $L/L_{\rm Edd}$ ratio. It appears that quasars tend to be in the 0.01–1 range, Seyferts in the 0.001–0.1 range, and NLS1s are all near Eddington with $L/L_{\rm Edd} \approx 0.1$–1.

3 The BH-Bulge relation

Compact dark masses, probably massive black holes (MBHs), have been detected in the cores of many normal galaxies using stellar dynamics (Kormendy & Richstone 1995). The MBH mass appears to correlate with the galactic bulge luminosity, with the MBH having about one percent of the mass of the spheroidal bulge (Magorrian *et al.* 1998, Richstone *et al.* 1998).

The question of whether AGN, and NLS1s in particular, follow a similar black hole -bulge relation is a very interesting one, as it may shed light on the connection between the host galaxy and the active nucleus.

Wandel & Mushotzky (1986) have found an excellent correlation between the virial mass included within the narrow line region (of order tens to hundreds of pc from the center) and the black hole mass estimated from X-ray variability in a sample of Seyfert 1 galaxies, while a group of Seyfert 2 galaxies systematically deviated from this relation. A black hole -bulge relation similar to that of normal galaxies has been reported between the MBH of bright PG quasars and their host galaxies (Laor 1998), but the mass of the elliptical host (or bulge, for spiral hosts) estimates have large uncertainties. A significantly lower black hole to bulge mass ratio has been found for the 17 Seyfert 1 galaxies with reverberation data (Wandel 1999). While the average is lower than the Magorrian *et al.* relation by a factor of 20, the record belongs to the NLS1 galaxy NGC 4051, for which Wandel (1999) finds a ratio that is a factor of 200 lower than the Magorrian *et al.* relation.

Apparently, this result suggests an intrinsic difference between the central black holes of Seyfert galaxies and those of normal galaxies. Actually the difference may be (at least partly) due to a selection effect. In angular-resolution limited methods (which are applied for detecting MBHs in normal galaxies), the MBH detection limit is correlated with bulge luminosity: more luminous bulges have a higher detection limit because the stellar velocity dispersion is higher (the Faber-Jackson relation). In order to detect the dynamic effect of a MBH, it is necessary to observe closer to the center, while the most luminous galaxies tend to be at larger distances. So, for a given angular resolution, the MBH detection limit is higher. Another effect could bias the PG quasars. Being the brightest nearby quasars, they may represent a subset of massive (and well-fed) black holes . Smaller ones would not appear as bright and would not be included in the quasar host galaxy survey.

The BLR method is not subject to this constraint, making Seyfert 1 galaxies good candidates for detecting low-mass MBHs. Seyfert 1 galaxies also have more reliable bulge mass estimates; as they are nearer and have a lower nuclear brightness, their host type and bulge magnitudes can be estimated more easily (Whittle 1992).

Finally, we concentrate on the difference between Seyfert 1 galaxies and NLS1s. NGC 4051, the only NLS1 in the sample of 17 Seyfert 1 galaxies with reverberation data, shows a dramatically lower black hole to bulge mass ratio and higher L/M ratio (Wandel 1999). Reverberation data on more NLS1s are required before one can conclude that NLS1s have intrinsically lower black hole to bulge mass ratios and smaller black holes.

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